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Carbon accumulation in cotton, sorghum, and underlying soil as influenced by tillage, cover crops, and nitrogen fertilization

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Abstract

Soil and crop management practices may influence biomass growth and yields of cotton (*Gossypium hirsutum* L.) and sorghum (*Sorghum bicolor* L.) and sequester significant amount of atmospheric CO_2 in plant biomass and underlying soil, thereby helping to mitigate the undesirable effects of global warming. This study examined the effects of three tillage practices [no-till (NT), strip till (ST), and chisel till (CT)], four cover crops [legume (hairy vetch) (*Vicia villosa* Roth), nonlegume (rye) (*Secale cereale* L), hairy vetch/rye mixture, and winter weeds or no cover crop], and three N fertilization rates (0, 60–65, and 120–130 kg N ha^{-1}) on the amount of C sequestered in cotton lint (lint + seed), sorghum grain, their stalks (stems + leaves) and roots, and underlying soil from 2000 to 2002 in central Georgia, USA. A field experiment was conducted on a Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults). In 2000, C accumulation in cotton lint was greater in NT with rye or vetch/rye mixture but in stalks, it was greater in ST with vetch or vetch/rye mixture than in CT with or without cover crops. Similarly, C accumulation in lint was greater in NT with 60 kg N ha^{-1} but in stalks, it was greater in ST with 60 and 120 kg N ha^{-1} than in CT with 0 kg N ha^{-1}. In 2001, C accumulation in sorghum grains and stalks was greater in vetch and vetch/rye mixture with or without N rate than in rye without N rate. In 2002, C accumulation in cotton lint was greater in CT with or without N rate but in stalks, it was greater in ST with 60 and 120 kg N ha^{-1} than in NT with or without N rate. Total C accumulation in the above- and belowground biomass in cotton ranged from 1.7 to 5.6 Mg ha^{-1} and in sorghum ranged from 3.4 to 7.2 Mg ha^{-1}. Carbon accumulation in cotton and sorghum roots ranged from 1 to 14% of the total C accumulation in above- and belowground biomass. In NT, soil organic C at 0–10 cm depth was greater in vetch with 0 kg N ha^{-1} or in vetch/rye with 120–130 kg N ha^{-1} than in weeds with 0 and 60 kg N ha^{-1} but at 10–30 cm, it was greater in rye with 120–130 kg N ha^{-1} than in weeds with or without rate. In ST, soil organic C at 0–10 cm was greater in rye with 120–130 kg N ha^{-1} than in rye, vetch, vetch/rye and weeds with 0 and 60 kg N ha^{-1}. Soil organic C at 0–10 and 10–30 cm was also greater in NT and ST than in CT. Since 5 to 24% of C accumulation in lint and grain were harvested, C sequestered in cotton and sorghum stalks and roots can be significant in the terrestrial ecosystem and can significantly increase C storage in the soil if these residues are left after lint or grain harvest, thereby helping to mitigate the effects of global warming. Conservation tillage, such as ST, with hairy vetch/rye mixture cover crops and 60–65 kg N ha^{-1} can sustain C accumulation in cotton lint and sorghum grain and increase C storage in the surface soil due to increased C input from crop residues and their reduced incorporation into the

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soil compared with conventional tillage, such as CT, with no cover crop and N fertilization, thereby maintaining crop yields, improving soil quality, and reducing erosion.

Introduction

Agricultural soils, being depleted of large amount of organic C due to cultivation, can be a significant sink of atmospheric CO_2 that helps to mitigate some of the effects of global warming (Lal and Kimble, 1997; Paustian et al., 1997). One of the practices to increase C sequestration in agricultural soils is to increase supply of C inputs from crop residues. A direct relationship exists between C input rates and soil organic C (Lal et al., 1980; Larson et al., 1972; Rasmussen et al., 1980). Carbon inputs can be added not only from aboveground but also from belowground biomass. Although aboveground biomass is mostly harvested, such as grains and lint for food and fiber and stems and leaves (or straws, stalks) for animal feed (hay), litter, or fuel, belowground biomass, such as roots, forms the main source of soil organic C. As much as 7–43% of the total above- and belowground plant biomass C can be contributed by roots (Kuo et al., 1997). Roots may play a dominant role in soil C cycle (Gale et al., 2000; Puget and Drinkwater, 2001; Wedin and Tilman, 1990) and may have relatively greater influence on soil organic C level than the aboveground plant biomass (Boone, 1994; Milchumas et al., 1985; Norby and Cotrufo, 1998). Balesdent and Balabane (1996) observed that corn (*Zea mays* L.) roots contributed 1.6 times more C to soil organic C than did by stover. When C contribution from rhizodeposition, such as root exudates, mucilages, and sloughed cells, along with roots was considered, corn root biomass contributed from 1.7 to 3.5 times more C to soil organic C than did by stover (Allmaras et al., 2004; Wilts et al., 2004). For accelerating soil C sequestration, crop residues, such as straws and stalks after grain or lint harvest, should be left in the soil instead of using them for other purposes.

Although crop biomass production is influenced by soil and environmental conditions, soil and crop management practices, such as tillage, cover cropping, and N fertilization, can significantly alter crop yields and biomass production, thereby altering C accumulation. Conservation tillage, such as NT or reduced till, can produce similar or higher cotton (*Gossypium hirsutum* L.) lint and sorghum (*Sorghum* bicolor L.) grain yields and biomass production than conventional till (Bordovsky et al., 1998; Nyakatawa et al., 2000; Torbert and Reeves, 1994). Similarly, legume cover crops can increase cotton lint and sorghum grain yields and biomass production compared with nonlegume or no cover crops because of increased N supply (Hargrove, 1986; Sainju et al., 2003; Touchton et al., 1984). Nitrogen fertilization also increases cotton and sorghum yields and biomass production (Sainju et al., 2003; Torbert and Reeves, 1994).

Little is known about the distribution of C in various components of crops and the effects of soil and crop management practices on them. Since crops can accumulate atmospheric C in stems, leaves, grains, lint, and roots through photosynthesis, it is essential to know C accumulation in these components grown under different management practices if the crop residue containing stems and leaves left after grain or lint harvest is used as amendments to increase C sequestration in soils. Although increasing lint or grain yields may result in the amount of crop residue returned to the soil, the magnitude of soil C sequestration depends on residue management practices, such as straw retention vs. removal, C allocation pattern in the crop, and rate of residue decomposition in the soil as influenced by tillage intensity (Kuo et al., 1997; Paustian et al., 1997). For example, increases in wheat (*Triticum aestivum* L.) yield have been obtained in the last several decades by allocating a substantial portion of C in the grain, which reduced residue production compared with yields (Cox et al., 1988). Similarly, residues with high C:N ratio or placed at the soil surface decompose slowly in the soil compared with low C:N ratio or incorporated into the soil (Quemada and Cabrera, 1995, Sainju et al., 2002; Staaf and Berg, 1981).

Tillage greatly influences soil organic C storage. While conventional tillage enhances mineralization of organic C by incorporating crop residue, disrupting soil aggregates, and increasing aeration (Balesdent et al., 1990; Cambardella and

Elliott, 1993; Dalal and Mayer, 1986), thereby reducing organic C level, NT can increase C storage in the surface soil (Allmaras et al., 2000; Jastrow, 1996; Sainju et al., 2002). However, organic C below 7.5 cm depth can be higher in tilled soil due to residue incorporation at greater depth (Clapp et al., 2000; Jastrow, 1996). Cover cropping can increase soil organic C compared with no cover cropping by supplying additional crop residue from its biomass in the spring before summer crop is planted (Kuo et al., 1997; McVay et al., 1989; Sainju et al., 2002). Similarly, N fertilization can increase soil organic C by increasing crop biomass production and amount of residue returned to the soil (Gregorich et al., 1996; Liang and McKenzie, 1992; Omay et al., 1997). Tillage can interact with cover cropping and N fertilization rate (Gregorich et al., 1996; Sainju et al., 2002; Wanniarachchi et al., 1999), soil texture and sampling depth (Ellert and Battany, 1995), and time since treatments were initiated (Liang et al., 1998) on soil organic C.

Our objectives were to: (1) examine the amount of C accumulation in cotton lint, sorghum grain, their stalks (stems + leaves) and roots, and underlying soil as influenced by tillage, cover crops (legumes and nonlegumes), and N fertilization rates from 2000 to 2002, (2) evaluate C accumulation in the belowground compared with aboveground biomass of cotton and sorghum, and (3) determine best management practices consisting of conservation tillage, cover crops, and N rates that sustain C accumulation in cotton lint, sorghum grain, and their above- and belowground biomass, and increase C sequestration in the soil.

Materials and methods

Field methods

The experiment was part of the long-term study of the effects of tillage, cover crops, and N fertilization rates on crop yields and soil quality conducted in 1995 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, Georgia, USA. Treatments consisted of three tillage practices [no-till (NT), chisel till (CT), and moldboard till (MT)], two cover crops [hairy vetch (V*icia villosa* Roth) and winter weeds or no cover crop], and three N fertilization rates (0, 60–90, and 120–180 kg N ha^{-1}) arranged in a split–split plot design with six replications. Tillage was the main plot, cover crop split plot, and N rate split-split plot treatment. Tomato (*Lycopersicum esculentum* Mill) was grown from 1995 to 1997 and silage corn (*Zea mays* L.) from 1998 to 1999. The soil was a Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults) with pH of 6.5 and sand content of 650, silt 250, and clay 100 g kg^{-1} soil at 0–30 cm depth. The clay content increased to 350 g kg^{-1} below 30 cm. Because cover crops and N fertilization rates did not influence soil organic C at 0–10 and 10–30 cm depths, organic C at 0–10 cm in October 1999 before cover crop planting, averaged across cover crops and N rates, was 12.3 Mg ha^{-1} in NT, 10.8 Mg ha^{-1} in CT, and 10.3 Mg ha^{-1} in MT. At 10–30 cm, organic C was 15.8 Mg ha^{-1} in NT, 15.9 Mg ha^{-1} in CT, and 15.7 Mg ha^{-1} in MT. Temperature and rainfall data were collected from a weather station, 20 m from the experimental site.

After corn harvest in October 1999, three replicates of winter weeds or no cover crop treatment were replaced by rye (*Secale cereale* L) cover crop and three replicates of hairy vetch (*Vicia villosa* Roth) were replaced by hairy vetch/rye mixture. In April 2000, the MT treatment was replaced by strip till (ST) which was considered as reduced till. In ST, rows were subsoiled to 35 cm depth in a narrow strip of 30 cm width for planting cotton (*Gossipium hirsutum* L.) and sorghum (*Sorghum bicolor* L.), thereby leaving the area between rows undisturbed. The surface tilled zone is leveled by coulters behind the subsoiler. The CT was considered as conventional till where plots were tilled with disc harrow and chisel plow. The NT plots were left undisturbed except for drilling cover crop, cotton, and sorghum seeds. Nitrogen rates of 0, 60–90, and 120–180 kg N ha^{-1} were replaced by 0, 60–65, and 120–130 kg N ha^{-1} according to the recommended N rates for cotton (120 kg N ha^{-1}) and sorghum (130 kg N ha^{-1}) in central Georgia. Thus the treatments established in October 1999 consisted of three tillage practices (NT, ST, and CT), four cover crops (hairy vetch, rye, hairy vetch/rye mixture, and winter weeds or no cover crop), and three N fertilization rates (0, 60–65, and 120–130 kg N ha^{-1}). These were arranged in a split–split plot design in randomized complete block, with tillage as the main plot, cover crop as the split plot, and N fertilization rate as the split–split plot treatment. Each treatment had three replications. The split–split plot size was 7.2 × 7.2 m.

Cover crops were planted in October–November, 1999 to 2001, in the same plot every year. Hairy vetch seeds were drilled at 28 kg ha^{-1} after inoculating with *Rhizobium leguminosarum* (bv. viceae) and rye seeds at 80 kg ha^{-1}, using a row spacing of 15 cm. In the hairy vetch/rye mixture, hairy vetch was drilled at 19 kg ha^{-1} (68% of monoculture), followed by rye at 40 kg ha^{-1} (50% of monoculture) in between vetch rows. The rates of hairy vetch and rye in the mixture were used as recommended by Clark et al. (1994). Cover crops were drilled in the plots without any tillage because previous studies have shown that cover crop aboveground biomass yields and C and N accumulations were not significantly influenced by tillage practices (Sainju et al., 2001, 2002). No fertilizers, herbicides, or insecticides were applied to cover crops.

In April, 2000–2002, cover crop biomass yield was determined by hand harvesting plant samples from two 1 m^2 areas randomly within each plot and weighed in the field. A subsample (≈100 g) was collected for determinations of dry matter yield and C and N concentrations and the remainder of the plant samples was returned to the harvested area where it was spread uniformly by hand. In the plots without cover crop, winter weeds, dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenolthera laciniate* Hill), were collected using the same procedure. Plant samples were oven-dried at 60 °C for 3 days, weighed, and ground to pass a 1-mm screen. After sampling, cover crops and weeds were mowed with a rotary mower to break the plants into smaller pieces and distribute the residue evenly within the plots. In NT and ST plots, cover crops were killed by spraying 3.36 kg ha^{-1} of glyphosate [N-(phosphonomethyl) glycine]. In CT plots, cover crops were killed by disc harrowing two to three times and chisel plowing. Residues were allowed to decompose in the soil for 2 weeks prior to cotton and sorghum planting.

At the time of planting cotton and sorghum in May, 2000–2002, P {from triple superphosphate [$Ca(H_2PO_4)_2$]} fertilizer at 36 kg ha^{-1} for cotton and 40 kg ha^{-1} for sorghum and K [from muriate of potash (KCl)] fertilizer at 75 kg ha^{-1} for cotton and 80 kg ha^{-1} for sorghum were broadcast in all plots based on the soil test and crop requirement. At the same time, B [from boric acid (H_3BO_3)] fertilizer at 0.23 kg ha^{-1} for cotton was also broadcast. Nitrogen fertilizer as NH_4NO_3 was applied at three rates (0, 60, 120 kg N ha^{-1}) for cotton in 2000 and 2002, half of which was broadcast at planting and other half broadcast at 6 weeks later. Similarly, NH_4NO_3 was applied at three rates (0, 65, 130 kg N ha^{-1}) for sorghum in 2001, two-third of which was broadcast at planting and other one-third broadcast 6 weeks later. The fertilizers were left at the soil surface in NT, partly incorporated in ST, and completely incorporated into the soil in CT by plowing. While NT plots were left undisturbed, ST plots were plowed in rows at 0.9 m apart, and CT plots were harrowed using a disc harrow two to three times until residues were broken into smaller pieces and soil particles loosened, followed by chiseling and leveling with a S-tine harrow.

Following tillage, glyphosate-resistant cotton (*Gossipium hirsutum* L, variety DP458BR) at 8 kg ha^{-1} in 2000 and 2002 and sorghum (*Sorghum bicolor* L., variety 9212Y) at 12 kg ha^{-1} in 2001 were planted in 8-row (each 7.2 m long) plots (0.9 m spacing) with a no-till driller. Although the experiment was planned to plant continuous cotton from 2000 to 2002, sorghum was planted in 2001 to reduce the incidence of diseases and pests. Cotton was sprayed with glyphosate at 3.36 kg ha^{-1} to control weeds immediately after planting and during cotton growth. For sorghum, atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] at 1.5 kg ha^{-1} and metolachlor [(2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide] at 1.3 kg ha^{-1} were applied within a day after planting to control post emergence of weeds. Aphids in cotton was controlled by spraying endosulfan (6, 7, 8, 9, 10-10-hexachloro-1, 5, 5a, 6, 9, 9a-hexahydro-6, 9 methano-2, 4, 3 benzodioxathiepin-3-oxide) at 0.6 kg ha^{-1}. Cotton was also sprayed with the growth regulator, Pix (1, 1-dimethyl-piperdinium chloride), at 0.8 kg ha^{-1} at 2 months after planting to control vegetative growth and the defoliant, Cottonquik

[1-aminomethanamide dihydrogen tetraoxosulfate ethephon (2-chloroethyl) phosphoric acid], at 2.8 l ha^{-1} a day after biomass collection and 2–3 weeks before lint and seed harvest to defoliate leaves. Irrigation (equivalent to 25 mm rain at a time using reel rain gun) was applied immediately after planting and fertilization and during dry periods to prevent moisture stress.

In October–November, 2000 and 2002, aboveground cotton biomass samples containing stems, leaves, and lint (including seeds) were hand harvested from two 1.8×1.8 m^2 areas randomly in places next to yield rows within the plot a week prior to the determination of lint yield. Biomass samples were weighed, chopped to 2.5 cm length, and mixed thoroughly, from which a representative subsample of 100 g was collected, oven-dried at 60 °C for 3 days, and ground to 1 mm for C analysis. Lint yield was determined by hand harvesting lint containing seeds from two central rows (7.2×1.8 m^2), separating lint and seeds after ginning, and weighing them separately. Similarly, in November 2001, aboveground sorghum biomass containing stems, leaves, and grains were collected from two 1.8×1.8 m^2 areas randomly in places next to yield rows within the plot, a week prior to the determination of grain yield. These were weighed, chopped to 2.5 cm length, and mixed thoroughly, from which a subsample of 100 g was oven-dried and ground to 1 mm for C analysis. Grain yield was determined by hand harvesting heads from two central rows (7.2×1.8 m^2), separating grains from heads, and weighing. Cotton lint containing seeds and sorghum grains were removed from the remaining plants within the plot from 2000 to 2002 using a combine harvester. After lint and grain harvest, both cotton and sorghum stalks containing stems and leaves were mowed and residues were left at the soil surface.

Within 2 weeks after mowing cotton and sorghum residues, soil samples were collected from 0- to 120-cm depth from each plot using a hydraulic probe [5 cm i.d. (internal diameter)] attached to a tractor to collect root biomass. Samples were collected from four holes, two in the rows and two in between, within each plot, composited, and stored at 4 °C until roots were separated from the soil. For analyzing soil organic C in 2002, 50 g of root-free soil samples from 0–10, 10–30, 30–60, 60–90, and 90–120 cm segments representing particular soil depths were collected from the soil core used for root separation, composited within a segment, air-dried, ground, and sieved to 0.1 mm. For measuring bulk density, a separate soil core (5 cm i.d.) divided into segments as above was taken, oven-dried at 105 °C, and weighed.

Laboratory analysis

Soil samples collected for determining root biomass were washed thoroughly with water in a nest of 1.0 and 0.5 mm sieves. About 500 g soil was washed at a time with a fine spray of water on the top and bottom sieves and roots retained on both sieves were picked by tweezers and collected in a plastic bag. As a result, all of the coarse and most of fine roots were collected. The process was repeated several times until all soil from a plot was washed and roots separated. Roots were oven-dried at 60 °C for 3 days, weighed, ground, and passed through a 1 mm sieve for C determination.

Total C concentration (g C kg^{-1} plant dry weight) in cotton lint, seeds, aboveground biomass (stems + leaves + lint + seeds), and roots and in sorghum grain, aboveground biomass (stems + leaves + grains) and roots was determined by using the C and N analyzer (LECO Co.). Similarly, total C and N concentrations in the aboveground cover crop biomass were determined by using the C and N analyzer. Carbon accumulation (kg ha^{-1}) in cotton lint and seeds, sorghum grain, and their aboveground biomass and roots was determined by multiplying dry matter weight by total C concentration. Carbon accumulation in cotton stalks (stems + leaves) was determined by subtracting C accumulation in lint and seeds from that in the aboveground biomass. Similarly, C accumulation in sorghum stalks (stems + leaves) was determined by deducting C accumulation in grain from that in the aboveground biomass. Carbon and N accumulations (kg ha^{-1}) in cover crop biomass were determined by multiplying dry matter weight by total C and N concentrations, respectively. Soil organic C concentration (g C kg^{-1}soil) was determined by C and N analyzer. Carbon storage (or organic C accumulation) in soil (kg ha^{-1}) was determined by multiplying organic C concentration by bulk density and soil depth.

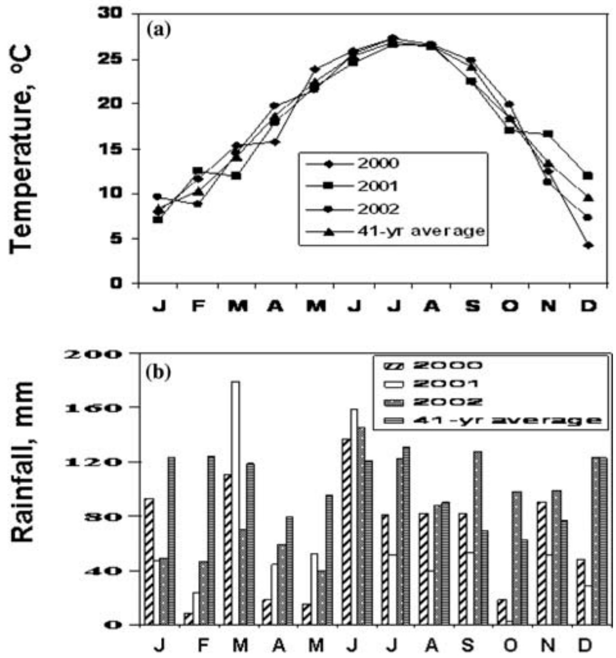

Figure 1. (a) Average monthly temperature and (b) total monthly rainfall from January to December in 2000, 2001, 2002 and the 41-year average near the study site.

Data analysis

Data for cover crop biomass yield, C and N accumulations, and C accumulation in cotton lint, sorghum grain, and their stalks and roots were analyzed using the MIXED procedure of SAS after testing for homogeneity of variance (Littell et al., 1996). Sources of variation included tillage, cover crop, N fertilization rate, and their interactions. Tillage, cover crop, and N fertilization rate were considered as fixed effects and replication and tillage × replication interaction were considered as random effects. Since the study was part of a long-term experiment where tillage plots were established in 1995, data for soil organic C in 2002 were analyzed separately for each tillage system. This is because significant difference in soil organic C at 0–10 and 10–30 cm depths were observed between tillage systems but the differences were not significant between cover crops and N rates when cover crops were planted in 1999. For this, sources of variation included cover crop (main plot treatment), N fertilization rate (split plot treatment), soil depth (split-split plot treatment), and their interactions. Data were analyzed using MIXED procedure as before. Means were separated by using the least square means test when treatments and their interactions were significant. Statistical significance was evaluated at $P \leq 0.05$.

Results

Climate

Average monthly temperature in May was higher in 2000 than in 2001, 2002, and the 41-year average but in September and October, the temperature was higher in 2002 (Figure 1a). Total monthly rainfall from July to November was higher in 2002 than in 2000 and 2001 (Figure 1b). Total rainfall during the growing season from May to November was also higher in 2002 (719 mm) than in 2000 (505 mm), 2001 (354 mm), and the 41-year average (645 mm). The temperature and rainfall during the growing season may influence growth of above- and belowground biomass and C accumulation in cotton and sorghum.

Table 1. Effects of years and cover crop species on aboveground biomass yield and C and N accumulations in cover crops averaged across tillage and N fertilization rates

Year	Cover crop[a]	Biomass yield (Mg ha^{-1})	Concentration (g kg^{-1})		Accumulation (kg ha^{-1})		C:N ratio
			C	N	C	N	
2000	WW	1.65	334	15	530	25	22
	R	6.07	388	15	2410	68	26
	V	5.10	354	33	1810	165	11
	VR	8.18	330	38	3170	310	9
2001	WW	0.75	353	20	250	15	18
	R	3.81	404	8	1560	32	51
	V	2.44	359	32	870	76	11
	VR	5.98	404	14	2430	84	29
2002	WW	1.25	338	18	430	23	19
	R	2.28	392	11	890	25	36
	V	5.16	326	36	1880	167	9
	VR	5.72	344	33	2040	186	10
LSD (0.05)[b]		0.96	34	7	480	23	6
Means							
2000		5.25a[c]	352a	25ab	1990a	96a	14ab
2001		3.25b	380a	19b	1280b	56b	20a
2002		3.60b	350a	32a	1310b	100a	11b
	WW	1.22c	342b	18b	400c	21c	19b
	R	4.07b	395a	12b	1640b	48c	33a
	V	4.23b	347b	34a	1520b	144b	10c
	VR	6.63a	359b	28a	2550a	186a	13bc

[a]Cover crops are R, rye; V, hairy vetch; VR, hairy vetch and rye mixture; and WW, winter weeds.
[b]Least significant difference between treatments at $P = 0.05$.
[c]Numbers followed by the different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

Cover crop biomass yield and carbon and nitrogen accumulations

Aboveground biomass yield and C accumulation were greater in cover crops than in winter weeds (Table 1). Biomass yield and C accumulation were greater in rye than in hairy vetch in 2000 and 2001 but were greater in vetch than in rye in 2002. The vetch/rye mixture had greater biomass yield and C accumulation than vetch and rye monocultures. Nitrogen concentration was higher in vetch and mixture than in rye and winter weeds. As a result, N accumulation was greater but C:N ratio was lower in vetch and mixture than in rye and weeds.

Carbon accumulation in 2000 cotton

Tillage, cover crop, N fertilization, and tillage $\times$ cover crop and tillage $\times$ N fertilization interactions were significant ($P \leq 0.05$) for C accumulation in cotton lint (including seeds), stalks (stems + leaves), and total components (lint + stalks + roots) in 2000. Carbon accumulation in cotton lint, averaged across N fertilization rates, was greater in NT with rye and vetch/rye mixture than in NT with vetch, ST with and without cover crops, or CT with vetch and vetch/rye (Table 2). In contrast, C accumulation in stalks was greater in NT with vetch and ST with vetch and vetch/rye than in NT, ST, and CT with weeds. Carbon accumulation in total components followed trends similar to C accumulation in stalks. Similarly, C accumulation in lint, averaged across cover crops, was greater in NT with 60 kg N ha^{-1} than in NT with 120 kg N ha^{-1}, ST with and without N rates, or CT with 60 and 120 kg N ha^{-1} (Table 3). Carbon accumulation in stalks and total components was greater in NT with 120 kg N ha^{-1} and ST with

Table 2. Effects of tillage and cover crops on C accumulation in cotton lint (including seeds), stalks (stems + leaves), roots, and total components (lint + stalks + roots) averaged across N fertilization rates in 2000

Tillage[a]	Cover crop[b]	C accumulation (Mg ha^{-1})			
		Lint	Stalks	Roots	Total
NT	WW	0.35	2.62	0.08	3.05
	R	0.47	3.78	0.07	4.32
	V	0.28	4.61	0.06	4.95
	VR	0.42	3.93	0.10	4.45
ST	WW	0.20	3.06	0.10	3.36
	R	0.29	3.98	0.05	4.32
	V	0.28	5.14	0.14	5.56
	VR	0.24	4.77	0.10	5.11
CT	WW	0.35	3.06	0.05	3.46
	R	0.36	3.29	0.13	3.78
	V	0.28	3.76	0.12	4.16
	VR	0.24	3.93	0.06	4.23
LSD (0.05)[c]		0.08	1.48	0.13	1.44
Means					
NT		0.38a[d]	3.74a	0.08a	4.20a
ST		0.25b	4.24a	0.09a	4.58a
CT		0.31b	3.82a	0.09a	4.22a
	WW	0.30b	2.96c	0.08a	3.34c
	R	0.37a	3.68b	0.07a	4.12b
	V	0.28b	4.50a	0.11a	4.89a
	VR	0.30b	4.21ab	0.09a	4.60ab

[a]Tillage is CT, chisel till; NT, no-till; and ST, strip till.
[b]Cover crops are R, rye; V, hairy vetch; VR, hairy vetch and rye mixture; and WW, winter weeds.
[c]Least significant difference between treatments at $P = 0.05$.
[d]Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

Table 3. Effects of tillage and N fertilization rates on C accumulation in cotton lint (including seeds), stalks (stems + leaves), roots, and total components (lint + stalks + roots) averaged across cover crops in 2000

Tillage[a]	N fertilization (kg ha^{-1})	C accumulation (Mg ha^{-1})			
		Lint	Stalks	Roots	Total
NT	0	0.36	3.28	0.10	3.74
	60	0.43	3.56	0.10	4.09
	120	0.35	4.37	0.04	4.76
ST	0	0.22	3.50	0.09	3.81
	60	0.28	4.54	0.05	4.87
	120	0.24	4.68	0.12	5.04
CT	0	0.36	3.08	0.07	3.51
	60	0.28	3.69	0.15	4.12
	120	0.27	3.76	0.06	4.09
LSD (0.05)[b]		0.08	1.04	0.11	1.20
Means					
	0	0.31ab[c]	3.28b	0.09a	3.68b
	60	0.33a	3.93a	0.10a	4.36a
	120	0.29b	4.27a	0.07a	4.63a

[a]Tillage is CT, chisel till; NT, no-till; and ST, strip till.
[b]Least significant difference between treatments at $P = 0.05$.
[c]Numbers followed by different letter within a column are significantly different at $P \leq 0.05$ by the least square means test.

60 and 120 kg N ha^{-1} than in NT, ST, and CT with 0 kg N ha^{-1}. Averaged across treatments, C accumulation in lint was greater in NT than in ST and CT, greater with rye than with vetch, vetch/rye, or weeds, and greater with 60 than with 120 kg N ha^{-1} (Tables 2 and 3). In stalks and total components, C accumulation was greater with vetch than with rye and weeds and greater with 60 and 120 than with 0 kg N ha^{-1}. In roots, C accumulation was not influenced by treatments and interactions.

Carbon accumulation in 2001 sorghum

In 2001, tillage, cover crop, N fertilization and cover crop × N fertilization interaction were significant ($P \leq 0.05$) for C accumulation in sorghum grains, stalks (stems + leaves), and total components (grains + stalks + roots). Carbon accumulation in grains, averaged across tillage, was greater in vetch/rye mixture with 65 and 130 kg N ha^{-1} than in rye and weeds with 0 and 65 kg N ha^{-1} (Table 4). Similarly, C accumulation in stalks was greater in vetch with 0 and 65 kg N ha^{-1}, vetch/rye with 65 and 130 kg N ha^{-1}, and weeds with 130 kg N ha^{-1} than in rye with 0 and 65 kg N ha^{-1} or weeds with 0 kg N ha^{-1}. Carbon accumulation in total components was greater in vetch with 0 kg N ha^{-1} and vetch/rye with 65 and 130 kg N ha^{-1} than in rye and weeds with 0 and 65 kg N ha^{-1}. Averaged across treatments, C accumulation in grains, stalks, and total components was greater with vetch and vetch/rye than with rye, greater with 130 than with 0 kg N ha^{-1}, and greater in ST and CT than in NT (Tables 4, Figure 2). Carbon accumulation in roots was not influenced by treatments and interactions.

Table 4. Effects of cover crops and N fertilization rates on C accumulation in sorghum grains, stalks (stems + leaves), roots, and total components (grains + stalks + roots) averaged across tillage in 2001

Cover crop[a]	N fertilization (kg ha^{-1})	C accumulation (Mg ha^{-1})			
		Grains	Stalks	Roots	Total
WW	0	1.02	3.87	0.10	4.99
	65	0.87	4.13	0.11	5.11
	130	1.30	5.37	0.10	6.77
R	0	0.56	2.73	0.10	3.39
	65	0.81	3.54	0.11	4.47
	130	1.21	4.41	0.11	5.73
V	0	1.22	5.64	0.07	6.93
	65	1.35	5.33	0.08	6.76
	130	1.34	4.83	0.10	6.27
VR	0	1.34	5.22	0.13	6.69
	65	1.57	5.36	0.13	7.06
	130	1.66	5.40	0.10	7.16
LSD (0.05)[b]		0.45	1.23	0.07	1.75
Means					
WW		1.06bc[c]	4.45bc	0.10a	5.61bc
R		0.86c	3.56c	0.11a	4.53c
V		1.27ab	5.27ab	0.08a	6.62ab
VR		1.52a	5.38a	0.12a	7.02a
	0	1.03b	4.37b	0.10a	5.50b
	65	1.15b	4.63ab	0.11a	5.89ab
	130	1.38a	5.00a	0.10a	6.48a

[a]Cover crops are R, rye; V, hairy vetch; VR, hairy vetch and rye mixture; and WW, winter weeds.
[b]Least significant difference between treatments at $P = 0.05$.
[c]Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

Carbon accumulation in 2002 cotton

In 2002, tillage, N fertilization, and tillage × N fertilization interaction were significant ($P \leq 0.05$) for C accumulation in cotton lint, stalks, roots, and total components. In contrast to 2000 cotton, with or without N rates, C accumulation in lint, averaged across cover crops, was greater in CT than in NT and ST (Table 5). Carbon accumulation in stalks was greater in ST with 60 and 120 kg N ha^{-1} than in NT with or without N rates. Carbon accumulation in roots was greater in ST with 60 kg N ha^{-1} and in CT with 120 kg N ha^{-1} than in NT with 0 kg N ha^{-1}. Carbon accumulation in total components was greater in ST with 60 and 120 kg N ha^{-1} and in CT with 0 and 60 kg N ha^{-1} than in NT with 0 kg N ha^{-1}. Averaged across treatments, C accumulation in lint was greater in CT than in NT and ST, in stalks was greater in ST than in NT, and in total components was greater in ST and CT than in NT. Similarly, C accumulation in lint was greater with 0 and 60 than with 120 kg N ha^{-1}.

Soil organic carbon

Cover crop, N fertilization rate, soil depth, and cover crop × depth, N rate × depth, and cover crop × N rate × depth interactions were significant ($P \leq 0.05$) for soil organic C measured after cotton harvest in NT, ST, and CT in 2002. Soil organic C at 0–10 cm depth in NT was greater in vetch with 0 kg N ha^{-1} or in vetch/rye with 120–130 kg N ha^{-1} than in weeds with 0 and 60–65 kg N ha^{-1} or vetch/rye with 0 kg N ha^{-1} (Table 6). At 10–30 cm, organic C was greater in rye and vetch/rye with 120–130 kg N ha^{-1} than in weeds with and without N rate, rye with 0 kg N ha^{-1}, or vetch with 120–130 kg N ha^{-1}. In ST, organic C at 0–10 cm was greater in rye and vetch/rye with 120–130 kg N ha^{-1} than in weeds, rye, and vetch/rye with 0 and 60–65 kg N ha^{-1} (Table 7). In CT, organic C at 0–10 cm was greater in vetch/rye with 60–65 kg N ha^{-1} than in weeds, rye, and vetch with 0 and 60–65 kg N ha^{-1} (Table 8). At 30–60 cm, organic C was greater in rye and vetch with 120–130 kg N ha^{-1} than in weeds with 0 kg N ha^{-1} or in rye with 0 and 60–65 kg N ha^{-1}. Averaged across N rates, organic C at 0–10 cm was greater in vetch than in vetch/rye in NT (Table 6) but was greater in vetch/rye than in weeds in ST and CT (Tables 7 and 8). Organic C at 30–60 cm was also greater in vetch/rye than in vetch in ST (Table 7). Averaged across cover crops, organic C at 0–10 cm was greater in 0 and 120–130 than in 60–65 kg N ha^{-1} but at 10–30 cm, it was greater in 0 than in 60–65 kg N ha^{-1} in ST (Table 7). In CT, organic C at 0–10 cm was greater in 60–65 than in 0 kg N ha^{-1} but at 10–30 cm it was greater in 120 than in 0 and 60–65 kg N ha^{-1} (Table 8). Averaged across cover crops and N rates, organic C at 0–10 and 10–30 cm was greater in NT and ST than in CT (Figure 3).

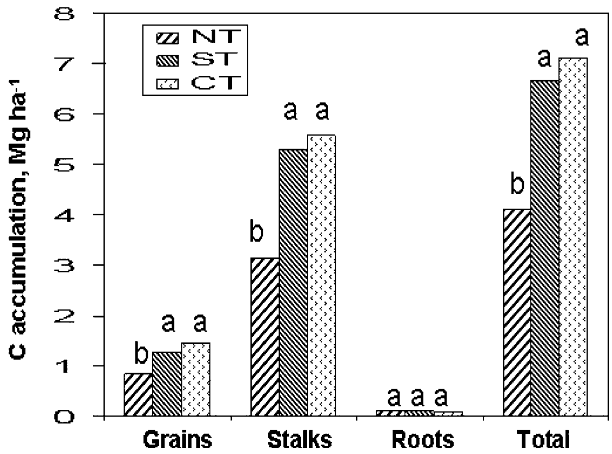

Figure 2. Effect of tillage on C accumulation in sorghum grains, stalks (stems + leaves), roots, and total component (grains + stalks + roots) in 2001. CT denotes chisel till; NT, no-till; and ST, strip till. Bars followed by same letter at the top are not significantly different by the least square means test at P ≤ 0.05.

Table 5. Effects of tillage and N fertilization rates on C accumulation in cotton lint (including seeds), stalks (stems + leaves), roots, and total components (lint + stalks + roots) averaged across cover crops in 2002

Cover crop[a]	N fertilization (kg ha^{-1})	C accumulation (Mg ha^{-1})			
		Grains	Stalks	Roots	Total
NT	0	0.28	1.24	0.17	1.69
	60	0.26	1.40	0.25	1.91
	120	0.20	1.50	0.27	1.97
ST	0	0.32	1.73	0.20	2.25
	60	0.31	2.07	0.28	2.66
	120	0.18	2.15	0.25	2.58
CT	0	0.62	1.75	0.22	2.59
	60	0.62	1.76	0.20	2.58
	120	0.61	1.53	0.28	2.42
LSD (0.05)[b]		0.13	0.53	0.10	0.70
Means					
NT		0.25b[c]	1.38b	0.23a	1.86b
ST		0.27b	1.99a	0.24a	2.50a
CT		0.62a	1.68ab	0.23a	2.53a
	0	0.41a	1.66a	0.20a	2.27a
	60	0.40a	1.74a	0.24a	2.38a
	120	0.33b	1.68a	0.27a	2.28a

[a]Tillage is CT, chisel till; NT, no-till; and ST, strip till.
[b]Least significant difference between treatments at $P = 0.05$.
[c]Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

Discussion

Because C concentration in various components of plants, such as stems, leaves, grains, and roots remains constant (Kuo et al., 1997; Sainju et al., 2002), C accumulation is generally proportional to the dry matter yield of the components. Since C sequestration in the soil is one of the media in the terrestrial ecosystem to reduce the concentration of CO_2 in the atmosphere and mitigate the deleterious effects of global warming, information on C accumulation in aboveground plant components, such as plant residue left after harvest in the soil, and belowground components, such as roots, that form important source of soil organic C is generally lacking. Because C concentration in cotton lint, stalks, and roots and sorghum grain, stalks, and roots was not influenced by treatments and interactions, only data on C accumulation in plant components will be reported.

Carbon accumulation among plant components varied with the species and environmental condition. In 2000 cotton, C accumulation in stalks ranged from 86 to 93% of the total C accumulation in lint, stalks, and roots (3.05–5.56 Mg ha^{-1}) and C harvested in lint ranged from 5 to 11%. In 2002 cotton, C accumulation in stalks ranged from 68 to 83% of total C accumulation (1.69–2.66 Mg ha^{-1}) and C harvested in lint ranged from 7 to 24%. In 2001 sorghum, C accumulation in stalks ranged from 75 to 81% of

Table 6. Effects of cover crops and N fertilization rates on organic C in no-tilled soil from 0- to 120-cm depth in 2002

Cover crops[a]	N rates[b]	Organic C in no-tilled soil (Mg soil C ha^{-1})				
		Soil depth (cm)				
		0–10	10–30	30–60	60–90	90–120
WW	NO	10.6	14.0	10.1	8.4	7.0
	NH	10.6	13.8	11.7	9.4	6.4
	NF	10.9	13.3	10.5	7.0	5.6
R	NO	11.1	14.1	10.3	7.9	5.3
	NH	11.1	15.6	10.3	8.1	5.8
	NF	11.5	17.1	11.3	6.6	6.8
V	NO	11.8	14.4	11.7	9.3	6.0
	NH	11.2	16.1	12.9	8.1	6.3
	NF	11.5	14.0	11.9	8.8	6.2
VR	NO	10.6	15.5	11.5	9.0	6.7
	NH	10.9	16.0	10.7	7.3	5.7
	NF	11.6	16.5	11.0	6.7	5.7
LSD (0.05)[c]		1.0	2.3	3.4	3.4	2.2
Means						
WW		11.0ab[d]	14.4a	10.6a	9.0a	6.3a
R		10.6ab	14.9a	10.4a	7.8a	6.2a
V		11.2a	14.9a	12.1a	8.7a	6.0a
VR		10.4b	14.4a	10.9a	7.7a	6.2a
	NO	11.0a	15.0a	11.6a	9.2a	6.4a
	NH	10.7a	14.6a	11.4a	8.2a	6.2a
	NF	10.6a	14.2a	9.9a	7.4a	6.0a

[a]Cover crops are R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds.
[b]N fertilization rates are NO, 0 kg N ha^{-1}; NH, 60 (cotton) to 65 (sorghum) kg N ha^{-1}; and NF, 120 (cotton) to 130 (sorghum) kg N ha^{-1}.
[c]Least significant difference between treatments at $P = 0.05$.
[d]Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

Table 7. Effects of cover crops and N fertilization rates on organic C in strip-tilled soil from 0- to 120-cm in 2002

Cover crops[a]	N rates[b]	Organic C in strip-tilled soil (Mg soil C ha^{-1})				
		Soil depth (cm)				
		0–10	10–30	30–60	60–90	90–120
WW	NO	9.7	13.7	9.9	6.9	6.1
	NH	8.8	14.0	10.1	8.0	5.6
	NF	10.2	15.5	9.4	8.3	5.6
R	NO	9.4	14.3	8.8	6.7	5.2
	NH	9.7	15.3	10.8	7.9	5.8
	NF	11.0	16.7	10.3	6.4	5.4
V	NO	10.0	14.3	9.7	6.5	5.8
	NH	9.9	14.5	9.2	6.5	5.7
	NF	10.3	15.9	9.0	6.4	5.5
VR	NO	9.0	14.7	10.1	8.4	4.9
	NH	9.1	14.9	10.6	7.3	5.4
	NF	10.8	15.1	10.3	7.9	6.6
LSD (0.05)[c]		1.0	2.8	3.0	3.3	2.1
Means						
WW		9.5b[d]	14.7a	10.3ab	8.1a	5.7a
R		10.1ab	15.4a	9.9ab	7.0a	5.6a
V		9.7ab	14.9a	9.2b	6.4a	5.4a
VR		10.3a	15.2a	11.7a	7.7a	5.5a
	NO	10.1a	16.0a	10.9a	7.2a	5.5a
	NH	9.3b	14.4b	10.2a	7.5a	5.3a
	NF	10.3a	14.7ab	9.8a	7.3a	5.8a

[a]Cover crops are R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds.
[b]N fertilization rates are NO, 0 kg N ha^{-1}; NH, 60 (cotton) to 65 (sorghum) kg N ha^{-1}; and NF 120 (cotton) to 130 (sorghum) kg N ha^{-1}.
[c]Least significant difference between treatments at $P = 0.05$.
[d]Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

total C accumulation (3.39–7.16 Mg ha^{-1}) and C harvested in grain ranged from 17 to 23%. Carbon accumulation in roots in 2000 cotton and 2001 sorghum ranged from 1 to 3% and in 2002 cotton ranged from 8 to 14%. Since a large portion of C accumulated in the plant is allocated in the stalk, C sequestration in the soil can be dramatically increased if stalks are left in the soil after grain or lint harvest. Although roots contributed a small portion of total C accumulation, they remain an important source of soil organic C because roots are usually left in the soil while aboveground biomass is removed. Soil C storage, however, depends on the amount of C input supplied by plant residue and its rate of decomposition. Greater C accumulation in cotton in 2000 than in 2002 was probably a result of higher amount of N supplied by hairy vetch or its lower C:N ratio (Table 1) and residual soil N which was not measured. In contrast, greater proportion of C accumulation in cotton roots in 2002 than in 2000 was probably resulted from increased rainfall during the growing season from May to November (Figure 1b), which may have promoted root growth.

Management practices significantly influenced C accumulation in cotton lint and stalks. For

Table 8. Effects of cover crops and N fertilization rates on organic C in chisel-tilled soil from 0- to 120-cm in 2002

Cover crops[a]	N rates[b]	Organic C in chisel-tilled soil (Mg soil C ha^{-1})				
		Soil depth (cm)				
		0–10	10–30	30–60	60–90	90–120
WW	NO	8.0	12.4	9.2	7.1	5.5
	NH	9.2	13.1	9.8	6.7	4.5
	NF	9.4	13.1	9.4	7.9	6.2
R	NO	8.9	12.9	8.8	7.6	6.0
	NH	9.0	13.7	9.1	7.1	5.8
	NF	9.1	14.0	12.1	8.1	5.9
V	NO	9.1	13.9	10.9	6.4	6.0
	NH	9.1	13.6	10.3	7.0	6.0
	NF	9.5	14.6	12.1	8.0	6.6
VR	NO	9.5	14.3	10.4	8.1	6.4
	NH	10.1	14.2	11.0	8.3	5.0
	NF	9.5	14.6	11.6	7.8	6.0
LSD (0.05)[c]		0.9	2.2	2.9	3.4	2.3
Means						
WW		8.8b[d]	12.8a	9.6a	7.5a	5.4a
R		9.3ab	14.2a	9.9a	7.5a	5.6a
V		9.2ab	13.4a	10.8a	6.9a	6.0a
VR		9.7a	13.9a	11.5a	8.1a	5.8a
	NO	8.9b	12.5b	10.1a	7.4a	5.9a
	NH	9.6a	13.4b	10.1a	7.3a	5.3a
	NF	9.3ab	14.8a	10.6a	7.9a	6.1a

[a]Cover crops are R, rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds.
[b]N fertilization rates are NO, 0 kg N ha^{-1}; NH, 60 (cotton) to 65 (sorghum) kg N ha^{-1}; and NF 120 (cotton) to 130 (sorghum) kg N ha^{-1}.
[c]Least significant difference between treatments at $P = 0.05$.
[d]Numbers followed by different letter within a column of a subset are significantly different at $P \leq 0.05$ by the least square means test.

example, while NT with rye or no cover crops and 0 kg N ha^{-1} increased C accumulation in cotton lint, NT or ST with vetch and vetch/rye mixture or with 60 and 120 kg N ha^{-1} increased C accumulation in stalks compared with other treatments in 2000 (Tables 2 and 3). Similarly, in 2002, CT with or without N rate increased C accumulation in cotton lint while ST with 60 and 120 kg N ha^{-1} increased C accumulation in stalks compared with other treatments (Table 5). Although soil N level at the time of planting cotton was not measured, excessive N application either from legume cover crop with lower C:N ratio (Table 1) or N fertilization probably reduced cotton lint yield and C accumulation at the expense of biomass yield and C accumulation, which increased with increased rate of N application. High rate of N fertilization can produce excessive vegetative growth that delays maturity and harvest and reduces cotton lint yield (Howard et al., 2001; Hutchinson et al., 1995; McConnell et al., 1993). Therefore, increasing C accumulation in cotton stalks by increasing N application rate may not be a good idea unless the objective is geared towards C sequestration in plants by increasing biomass yield, because the main objective in cotton production system is to increase lint yield. Sustainable lint yield and biomass C accumulation, however, can be achieved by reducing N application either through using cover crops, such as using vetch/rye mixture instead of vetch, or reduced rate of N fertilization, such as 60 instead of 120 kg N ha^{-1}, which also improves environmental quality by reducing N leaching.

In contrast to cotton, N application from legume cover crop or N fertilization increased C accumulation both in sorghum grains and stalks compared with nonlegume or no cover crop and no N fertilization in 2001 (Table 4). This is probably because both grains and stalks respond equally to N application in increasing yields. Increase in sorghum grain and biomass yield with increased application of N from legume cover crops and N fertilization were observed by several researchers (Hargrove, 1986; McVay et al., 1989). Similar levels of C accumulation in grains and stalks in vetch and vetch/rye mixture with 0 kg N ha^{-1} and in rye and weeds with 130 kg N ha^{-1} suggests that both vetch and vetch/rye can supply full N requirement for sorghum without any additional need of N fertilizer. Similarly, lack of difference in C accumulation in grains and stalks between vetch and vetch/rye treatments suggests that vetch can be replaced by vetch/rye to sustain sorghum yield and C accumulation and reduce N leaching, because vetch/rye mixture is more effective in reducing N leaching than vetch alone (McCracken et al., 1994; Meisinger et al., 1990).

The effects of tillage on C accumulation in cotton lint varied. In 2000, C accumulation in lint was greater in NT than in ST and CT but in 2002, it was greater in CT than in NT and ST (Tables 2 and 5). Carbon accumulation in cotton

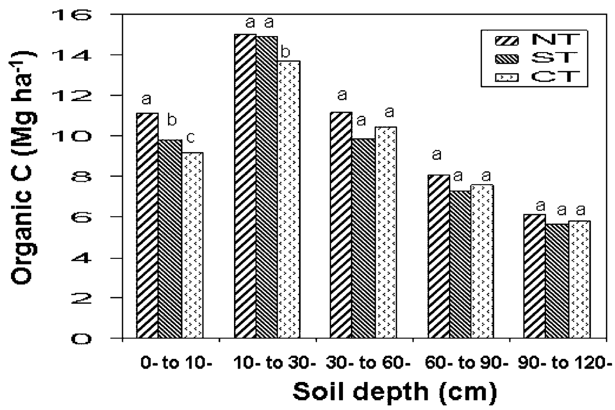

Figure 3. Effect of tillage on soil organic C at 0–120 cm depth in 2002. CT denotes chisel till; NT, no-till; and ST, strip till. Bars followed by same letter at the top are not significantly different by the least square means test at $P \leq 0.05$.

stalk, however, was greater in ST than in NT and CT in both years. Similarly, C accumulation in sorghum grain and stalk was greater in ST and CT than in NT (Figure 2). This suggests that reduced tillage, such as ST, can be used to increase C accumulation in cotton and sorghum biomass. Although root growth was not influenced by tillage, subsoiling to a depth of 35 cm, thereby breaking the hardpan layer below 30 cm in the soil profile could have promoted stalk growth of cotton and sorghum in ST compared with NT and CT.

Cover crops and N fertilization rates influenced soil organic C storage in NT, ST, and CT by affecting the amount of C inputs returned to the soil from the residue due to difference in biomass production. While greater levels of C input were returned from cover crops than from weeds or from vetch/rye mixture than from vetch or rye, increased N supply from vetch and vetch/rye mixture with their lower C:N ratio [which indicates their rapid rate of decomposition in the soil compared with higher C:N ratio of rye or weeds (Table 1)] and from increasing N fertilization rates increased biomass production and C accumulation in cotton and sorghum stalks compared with rye and weeds and no N rate (Tables 1–5). As a result, soil organic C at 0–10 and 10–30 cm depths were also greater in cover crops than in weeds, with than without N rate, and in cover crops with 120–130 kg N ha^{-1} than with 0 and 60 kg N ha^{-1}, or in weeds with or without N rate (Tables 6–8). Increased C sequestration in soil with cover crops and N fertilization compared with no cover crops and N fertilization has been reported by several researchers (Gregorich et al., 1996; Kuo et al., 1997; Omay et al., 1997; Sainju et al., 2000). Soil C storage below 60 cm depth, however, was not influenced by treatments, probably because the small amount of roots found at these depths did not supply enough C input to change soil organic C level.

Because of the variation in C accumulation in cotton and sorghum stalks and placement of their residue in the soil due to tillage, soil organic C at 0–10 and 10–30 cm depths also varied. Although C accumulation in cotton and sorghum stalks were lower in NT than in ST and CT (Tables 2 and 5), placement of their residue at the soil surface, thereby reducing their contact with soil microorganisms, may have increased soil organic C at 0–10 cm in NT compared with ST and CT (Figure 3). In contrast, incorporation of residues into the soil to a greater depth, thereby increasing their rate of decomposition, may have decreased soil organic C at 0–10 and 10–30 cm in CT compared with NT and ST. Increased C accumulation in cotton and sorghum stalks, followed by reduced incorporation of their residues into the soil, may have increased soil organic C in ST than in CT. Increased soil organic C in NT compared with conventional tillage at depth < 7.5 cm are well known (Allmaras et al., 2000, 2004; Claap et al., 2000; Jastrow, 1996).

From 2000 to 2002, soil organic C decreased by 9.8% in NT, 4.8% in ST, and 14.8% in CT at 0–10 cm. At 10–30 cm, soil organic C decreased by 5.1% in NT and ST and 13.8% in CT. Although C inputs were added from cover crop, cotton, and sorghum residues, tillage intensity probably has greater influence on soil organic C level than the amount of C inputs added, because greater percentage of soil organic C between 2000 and 2002 was lost from CT than from NT and ST at 0–10 and 10–30 cm depths. Replacing MT by ST in 2000 dramatically reduced soil organic loss within 3 years, because the percent loss of soil organic C from 2000 to 2002 was lower in ST than in CT. Therefore, increasing the amount of C input from plant residue and reducing its rate of decomposition by deceasing tillage intensity using conservation tillage, cover crops, and N fertilization can significantly increase soil C sequestration compared with conventional tillage with no cover crop and N fertilization.

A combination of management practices that include conservation tillage, such as ST, with a mixture of legume and nonlegume cover crops and reduced rate of N fertilization can be used to sustain C accumulation in cotton and sorghum, increase soil C sequestration, and improve environmental quality by reducing soil erosion and N leaching compared with conventional tillage with no cover crops and N fertilization if the stalks are left in the soil after lint or grain harvest. Removing aboveground biomass of crops can significantly reduce soil organic C (Kuo and Jellum, 2002; Wilts et al., 2004). Regardless of the management practices used, C sequestration in crop production system and underlying soil remains an important part of global C sequestration in the terrestrial ecosystem. A C credit system should be encouraged to produce greater stalk production besides increasing crop yields using appropriate management practices that leave the stalks in the soil so that atmospheric C sequestration in the plant and soil can be increased.

Conclusions

Carbon allocation in plant components and sequestration in underlying soil was influenced by crop species, management practices, and environmental conditions. Carbon accumulation in cotton stalks ranged from 68 to 93% of the total C accumulation in lint, seeds, stems, leaves, and roots (1.69–5.56 Mg ha^{-1}) and in sorghum stalks ranged from 75 to 81% of the total C accumulation in grains, stalks, and roots (3.39–7.16 Mg ha^{-1}). Carbon accumulation in cotton and sorghum roots ranged from 1 to 14%. Nitrogen applied from legume cover crop or N fertilization decreased C accumulation in cotton lint but increased in stalks. In contrast, N applied from legume cover crop or N fertilization increased C accumulation in both sorghum grains and stalks. Carbon accumulation in lint was greater in NT than in ST and CT in 2000 but was greater in CT than in NT and ST in 2002. Carbon accumulation in cotton stalks and sorghum grains and stalks was greater in ST than in CT. Increased rainfall increased C accumulation in cotton roots in 2002 than in 2000. Soil organic C at 0–10 and 10–30 cm depths was greater in cover crops with 120–130 kg than in winter weeds with 0 and 60–65 kg N ha^{-1} and greater in NT and ST than in CT. Conservation tillage, such as ST, with a mixture of legume and nonlegume cover crops and 60–65 kg N ha^{-1} can be used to increase C accumulation in cotton and sorghum biomass, sustain lint and grain yields, increase soil C sequestration, and improve environmental quality by reducing soil erosion and N leaching compared with CT with 120–130 kg N ha^{-1} and no cover crops. Because of higher C accumulation, stalks of cotton and sorghum, if left after lint or grain harvest, may substantially increase C sequestration in the soil.

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